

Host galaxies of 2MASS-selected QSOs at redshift over 0.3 ¹

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ABSTRACT

We have obtained optical imaging with the Canada France Hawaii Telescope (CFHT) of 21 2MASS-selected QSOs of redshift greater than 0.3. This paper complements the sample of lower redshift 2MASS QSOs previously published. The QSOs have higher overall and nuclear luminosity, bluer colours, and higher ratio of nuclear to host flux than the lower redshift sample. From these and other properties, we argue that the sample is consistent with the emergence of the AGN from dusty starbursts following major tidal interactions between galaxies.

Subject headings: galaxies:quasars

1. Introduction and observations

This paper is a sequel to the paper by Hutchings, Maddox, Cutri, and Nelson (2003: paper 1), which presented optical imaging of QSOs of redshift 0.3 and lower, selected from the Two Micron All Sky Survey (2MASS). HST imaging of a different sample of 2MASS QSOs is given by Marble et al (2003). In this paper we present optical imaging of a sample of 2MASS QSOs at redshifts above 0.3. The sample of QSOs is the same as in paper 1, but with the higher redshift bin.

The QSOs are identified by spectroscopy after selection by colours J-K larger than 2.0, and are classified as types 1, 2 or intermediate, based on the ratio of narrow to broad line emission. These do not include any previously known AGN. 2MASS QSO selection is described in Cutri et al. (2002). The present study includes objects between -30° and 60° declination, and thus suitable for observation with the CFHT. Paper I included data on 76 of 243 eligible objects, and this paper includes data on 21 of 64 eligible objects. All but 2 of the eligible objects have redshifts below 0.7.

The observations were taken as service-observing ‘snapshots’ with the Megaprime camera and r-band filter, with exposures of 340 secs. The pixel sampling is 0.187 arcsec. (The paper 1 data were taken with R band, and 0.206 arcsec sampling, and 200 sec exposures, with the CFHT 12K camera. The CFHT website gives details of the different filters.) All objects had two independent images, 5 had four images, and two had 8 images. The data were obtained over the period April through June 2004, in seeing conditions that varied from 0.6 to 1.3 arcsec FWHM. Table 1 lists the objects observed, and various of their properties, from the 2MASS database and also measures from the present work.

As the selection of observed objects was dictated mainly by scheduling, we show in Figure 1 the distribution of observed objects within the whole sample of 64 high redshift objects, and also include the lower redshift sample from paper 1. The observed subsample

is slightly skewed to higher luminosity, but there is K-band luminosity overlap of about 15 new objects with 21 of the highest luminosity objects from the lower redshift sample. In terms of J-K colour, the observed subset is slightly skewed to redder objects than the average by about 0.5 magnitudes. The spectral classifications among the new sample are representative of the 2MASS QSOs in this redshift range.

2. Data processing and measurements

After removal of the instrumental signature, subimages were generated of each QSO and 3 PSF stars from the same CCD and observation, as near as possible to the QSO. The two (or more) images of each field were combined, to help remove cosmic rays and to increase the signal. In a couple of cases, some of the images had very different FWHM as they were taken on different nights, and such images were not combined.

PSF stars were chosen to have more signal than the QSOs, and to be free of nearby companions and image flaws. Any other stars near the PSF stars were edited out of the images before generating the profiles, to get the most representative PSF profiles. The images and luminosity profiles were compared among the PSF stars, and generally the cleanest one was picked as the PSF to be used. Occasionally two PSF stars were co-added, to increase the signal, after checking that the profiles agreed.

Measurements were made of every individual image, as well as the combined images, to give independent values of the fluxes and PSF-removal. The measurements made were the flux of the QSO and the PSF stars, and the image FWHM from profiles. Profiles were generated by the IRAF task ellipse, after careful sky removal. Companions near the QSOs were included in their profiles, although in some cases, well separated companions were edited out to better study the extended flux centered on the QSO. Figure 2 shows profiles

from one object as an example.

The host galaxy fluxes were estimated in two ways. First, the flux difference was measured between the QSO and PSF profiles, after scaling the PSF profile to the same peak value as the QSO. This yields a measure of the resolved flux which is a lower limit to the QSO host flux. Second, differently scaled PSF images were subtracted from the QSO to yield a resulting profile that increases monotonically to the nucleus. The value for the profile that just turns over near the nucleus yields an upper limit for the host galaxy flux. The best value was taken to be the intermediate case where the difference flux follows a smooth profile for its inner part. While this was subjective, and depends in principle on whether the difference follows an exponential or de Vaucouleurs profile, or combination, the QSO nuclear flux was generally small enough that the spread in these difference fluxes was small. Error bars were taken for each host galaxy flux as the upper and lower values described above.

The same procedure was repeated for the co-added images for each QSO. Table 1 shows the final adopted values for the ratio of nuclear to resolved flux for each QSO. The agreement between the individual and the combined images was in all cases within 20%, and the ranges as described above have similar values. Thus, in Table 1 we show the mean values (average discarding outliers) for the nuclear to flux ratio, and we assign an overall uncertainty of 30% in those values. Note that the resolved flux given does not include any separate close companions within the radius of 10 arcsec: where these are present they were not included. The resolved flux does include any features that appear to be part of or connected to of the host galaxy, even though they introduce irregularities into the azimuthally averaged profile. Many of the profiles are irregular, which means that fit to either standard model is somewhat arbitrary. We have noted where the profiles do have some region of good fit to one or other model. There are ten with some spheroidal

component and four with a good exponential. Four others have so many companions that no fit is good, and another three are clean but do not have clean regions of good fit. In several cases, the host galaxy appears to have both bulge and disk components to the azimuthally averaged profile.

The morphology of the QSO images, both raw and PSF-subtracted, was inspected to make an estimate of the degree of tidal disturbance. As in paper 1, this value takes into account the presence of connecting bridges to companions, single asymmetric arms or extensions, radial jet-like features, warps, and other asymmetries. This is quantified as an interaction strength index from 0 to 3, as in paper 1. Two objects have archival HST images from Marble et al 2003 (the last and third last ones in Table 1). In the first of these, no interaction is seen in either telescope image. In the second, our CFHT image has some asymmetry (interaction index 1), but the HST image shows considerable structure that clearly indicates a significant disturbance on small scales (see Figure 3). Thus, our interaction indices may well be conservative. Figure 3 shows examples of the three levels of interaction, plus an HST image for comparison.

3. Results

All the QSOs in the sample are resolved, most of them easily, with ratio of nuclear to resolved flux ranging from 0.17 to 25. We discuss the properties of the resolved flux in the subsections below, but begin with a look at possible biases and selection effects within the dataset.

3.1. Biases and systematics

Since there is a range of image quality in the sample (from 0.6 to 1.3 arcsec), we looked for measured quantities that may depend on it. The image quality shows no correlation with object redshift. The interaction index shows no envelope or correlation. The ratio of nuclear to resolved flux also does not show any trend, and certainly not in the expected sense of lower ratios for better seeing. The dynamic range of ‘useful’ QSO image does show an upper envelope where the maximum range is smaller for larger FWHM images. This is largely the effect of reducing the peak central signal with poor image resolution, and the limiting signal is not affected. Overall, for the sample and measurements we discuss, the image quality is not very important and is not introducing any significant bias to the results.

Another observational variable is the total exposure time. While most objects have 680 secs integration, three have twice that, and two have four times that. The interaction index, and useable dynamic range are not correlated with the exposure, and the two best-resolved objects have the minimum exposure. Thus, exposure time is not biasing the overall results of the work.

The mix of spectral types is not correlated with object redshift. The magnitude of the QSO is not correlated with the dynamic range of the images. The least resolved objects are not the highest redshift ones, so there is no observational bias obvious. The median ratio of nuclear to resolved flux is 4, and values near this are spread evenly across the redshift range. There is no systematic colour change with redshift, or change of scale length with redshift, so the mix of objects appears to be unrelated to redshift.

3.2. Nucleus to host ratio

Figure 4 shows the ratio of nuclear to resolved flux with spectral class. The ratio increases with the dominance of the broad emission line components, which is as expected for the general model of central obscuration by a torus for type 2 objects.

The lowest dynamic range observations have the lowest nuclear light domination. This means that the resolved flux is in the inner parts of the host galaxies, and that low nuclear domination is caused by obscuration within the central host galaxy. However, overall QSO colour is loosely correlated with nuclear domination, so the obscuration is connected with reddening of the nuclear light - a separate phenomenon from the obscuration of line emission by the torus.

The result that obscuration is connected with the diminishing of the nuclear light in the optical is supported by the findings of Francis, Nelson and Cutri (2004) who found that a number of near-ir flux-selected AGN were missed in SDSS because their optical colors were indistinguishable from normal galaxies. They speculated this was because the nuclei were preferentially reddened and thus better visible in the near-ir.

Scale length of the host galaxy is not correlated with nuclear domination, so the nuclear region is obscured without affecting the outer parts of the host galaxy. Scale length is also not related to the spectral class or the colour of the QSO. Further mention is made of the scale length below.

3.3. Interaction status

The level of interaction seen is not strongly related with the QSO colour, but there is a trend towards redder colour for more strongly interacting systems. There is a clear dependence and upper envelope with the nuclear fraction, in the sense that the more

interacting objects have more obscured nuclei (see Figure 5).

It is also clear that interactions are less obvious in higher redshift objects, as expected as the signal to noise and the angular scales decrease. We note that the object with HST imaging, given interaction class 1 from the CFHT data, is clearly interacting in the HST images, and would have index 2. Thus, the CFHT interaction indices should be regarded as lower limits overall, and particularly for the higher redshift objects.

The host galaxy scale length shows a trend where they are larger for weaker interacting systems, although there is considerable spread. This will reflect the presence and decay of disks, tidal arms, and eventual increase in spheroid structure during a major interaction.

Comparison with the $z < 0.3$ sample in paper 1 is of interest. Figure 6 shows the fractions with interaction index with redshift in different QSO samples, where the 2MASS lower redshift sample is large enough to split at $z = 0.2$. There is a systematic shift towards lower interaction index with increasing redshift. Even allowing for lowering the index by one grade point for 1/2 of them (which would allow for missed signatures seen only with higher resolution, as is Figure 3), we find the interactions are stronger at lower redshifts. Since the higher redshift objects are more luminous, it may be that the more interacting and hence more obscured objects are not detected in the higher redshift bins because of flux limits. The ratio of counts of objects above and below $z = 0.3$ (64 to 243, plus lack of LINERS at $z > 0.3$), shows the 2MASS flux limitation clearly.

3.4. Radio flux

Six of the sample of 21 appear in the FIRST radio catalogue (although 2 of them are too far south to appear in the FIRST catalogue: see Becker et al 1995). They are all unresolved, and faint - see Table 1 for the fluxes. The mean redshift of the radio sources

is the same as that for the others (~ 0.40). There is no correlation between radio flux and colour. The mean ratio of nucleus to host for the radio sources is 2.5, compared with 7.2 for the others (medians 1.3 and 3.2). The spectroscopic types have the same (full) spread for radio and radio-quiet objects. The radio sources have an average interaction index of 2 while the others have value 1, and this difference is significant at the 95% level, if the distributions are gaussian. This suggests that nuclear radio sources occur in recently activated nuclei where the signs of interaction, and dust obscuration are higher. This is similar to the result on IRAS galaxies investigated by Neff and Hutchings (1992).

3.5. Asymmetries and profiles

The ellipticities of the contours in this sample are lower than those in paper 1, and follow the same upper limit which decreases with increasing redshift. This is largely the effect of the diminishing scale and surface brightness with redshift, but the values are less determinate as the presence of line of sight companions increases too.

Profiles were classified as good fits to $R^{1/4}$ law or exponentials if they had significant linear sections in the relevant plots. Many objects have nearby companions or asymmetries which made these simple classifications impossible. However, there were 3 objects with good exponential profile sections and 9 with good bulge components. Their mean redshifts are 0.38 and 0.43, respectively, so that the outer exponential tails may simply be less detectable in the fainter higher redshift objects.

It is of interest to compare the profiles of an object with HST imaging (1715+281). The HST image shows strong asymmetry of the resolved flux and is traceable to a radius of $2.4''$, while the CFHT image shows less of the structure but the same asymmetry out to $7''$ (see Figure 2). The profiles agree and both indicate that $r^{1/4}$ fits quite well, while an

exponential does not. Thus, there is good agreement in this one case of overlap with HST data.

3.6. Scale lengths

The scale lengths given in Table 1 are derived from the slopes of the radius-magnitude plots for the images, outside the unresolved cores. They do not include any significant companions, and are converted to Kpc for a Hubble constant of 75. Cases where the slope cannot be measured with any reliability are left blank. Scale length is not correlated with the dynamic range of the images, although the latter range only by about 25%. It is also not correlated with the image quality - as expected since the profiles are azimuthally averaged over values far greater than the image quality.

The scale length is larger for the more interacting systems. This is a quantitative measure of the extended arms and asymmetries that lead to the higher interaction indices. In general the scale length values are comparable with large nearby galaxies.

4. Discussion

In paper 1 we noted a number of differences between the 2MASS low redshift QSOs and standard blue QSOs. Generally speaking, the 2MASS objects are redder and have more obscured nuclei, and the host galaxies show a far greater proportion of tidal interactions.

We note that the 2MASS sample requires detection in all three of the JHK passbands, so that there is a bias against highly reddened objects. The J-K colours average at 2.2 mag in both the lower and higher redshift subsamples, but the B-R colours are different, as seen in Table 2. The selection will also lose the less luminous objects as the redshift increases.

While this is clearly true from Figure 1, it is interesting to note the large fraction of more luminous objects that appear at higher redshifts. This increase is just what is expected from the 6-fold increase in volume of space sampled, so there may not be significant selection effects between the present sample and the lower redshift objects in paper 1.

In most of the aspects considered, the higher redshift 2MASS objects are more similar to ‘normal’ blue-selected QSOs, but they are intermediate between them and the low redshift 2MASS QSOs. Table 2 shows some key comparison numbers, based on paper 1 and the optically selected sample of Hutchings and Neff (1991).

The higher redshift sample of this paper correspond to the highest luminosity objects in paper 1. The subset of the paper 1 objects that match this K-band luminosity are also shown in Table 2, and they have higher nucleus to host ratio and bluer colour than the full paper 1 sample, but not as high or blue as the sample in this paper. Thus, luminosity is a relevant parameter as well as redshift. The single high redshift object (at $z=2.37$) has very high luminosity (although optical emission lines shifted into the 2MASS bandpasses probably contribute), and is hardly resolved in our data. Thus, there is probably nothing very remarkable in this object from the data presented here.

The higher redshift (and luminosity) sample of this paper is generally similar to normal blue QSOs, but still have a higher fraction of interaction evidence, although the fraction of highly interacting objects is similar to that for blue QSOs. This is seen in both morphology and luminosity profiles. It seems likely that the higher luminosity QSOs blow away the circumnuclear dust faster, but are still relatively young AGN. The unresolved nature of the radio sources is consistent with this idea.

The sample does not reach the faint luminosities of the low redshift objects in paper 1, so the evolution of these sources cannot be traced until we have a deeper NIR QSO survey. We note that the Spitzer telescope has reported finding a large population of lower

luminosity AGN in their deeper survey. It will be important to follow those up with high resolution imaging.

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References

- Becker, R., White R.L., and Helfand D.J., 1995, ApJ, 450, 559
- Cutri, R.M. et al, 2002, ASP Conf Ser vol 284, 127
- Francis P.J., Nelson B.O., and Cutri, R.M., 2004, AJ, 127, 646
- Hutchings J.B., Maddox N., Cutri R.M., Nelson B.O., 2003, AJ, 126, 63 (paper 1)
- Hutchings J.B. and Neff S.G., 1992, AJ, 101, 434
- Marble A.R. et al., 2003, ApJ, 590, 707
- Neff S.G. and Hutchings J.B., 1992, AJ, 103, 1992

Table 1. 2MASS QSO sample

RA	Dec	z	Typ a	B, R, J, H, K	N/H b	Int c	Sc L Kpc ^d	Range mag ^e	20cm mJy	IQ ” ^f	M _K
11 03 12.93	41 41 54.9	0.403	1.2	16.6,16.1,15.2,14.2,13.0	16.6	1.	–	9.5	–	1.1	-29.1
13 32 31.17	03 59 28.0	0.346	1.	17.4,17.3,16.0,14.8,13.4	4.3	1.	–	11.3	1.5	0.9	-28.3
13 45 17.89	-08 29 57.3	0.473	1.	–, –, 15.6,14.2,12.8	3.9	2.	7.7	9.6	–	0.8	-29.6
14 32 04.62	39 44 38.9	0.349	1.5	16.4,16.3,16.0,15.4,14.4	5.4	1.	4.4	8.5	–	0.8	-27.3
14 35 15.66	02 32 21.7	0.305	1.2	16.6,16.7,15.6,14.4,12.9	12.	1.	–	11.5	–	0.9	-28.5
14 38 27.94	-11 22 49.5	0.401	1.5	19.6,18.7,16.3,15.1,13.6	1.2	1.	8.6	9.0	–	1.1	-28.4
14 41 18.87	-11 31 47.5	0.330	1.2	16.6,16.8,16.2,15.2,14.0	2.5	1.	4.8	10.5	–	1.0	-27.6
14 42 02.95	14 55 39.3	0.307	1.2	17.6,17.0,16.2,15.2,14.2	1.8	3.	5.9	10.4	104.	0.9	-27.2
14 50 00.90	14 29 48.7	0.358	1.2	17.7,17.1,16.4,15.6,14.4	12.	0.	–	12.0	–	0.7	-27.4
15 00 13.40	12 36 45.2	0.407	1.9	19.5,18.9,16.8,15.9,14.6	0.3	3.	4.7	8.1	–	0.8	-27.5
15 01 50.51	49 33 38.2	0.337	1.9	18.1,17.1,16.4,14.9,13.5	0.26	3.	4.8	8.0	3.1	0.8	-28.2
15 31 07.19	12 08 14.4	0.542	1.5	19.8,18.7,17.1,15.7,14.6	3.2	2.	6.7	10.2	–	1.0	-28.1
15 36 44.92	14 12 29.4	0.399	1.2	16.7,17.3,16.1,15.4,14.0	4.8	2.	6.6	10.5	–	0.9	-28.0
15 40 19.57	-02 05 05.3	0.319	1.	16.0,15.8,15.3,14.3,13.2	6.	2.	4.7	9.3	4.7	1.0	-28.3
15 49 38.73	12 45 09.2	2.37	1.9	18.7,17.3,15.8,14.5,13.5	25.	0.	–	12.5	–	0.7	-33.0
15 50 59.30	21 28 08.8	0.373	1.	17.3,16.8,16.3,15.7,14.3	8.8	0.	–	12.8	–	0.6	-27.6
16 18 09.74	35 02 08.9	0.446	1.9	18.8,18.2,16.8,15.4,14.1	2.6	2.	6.9	10.0	14.	0.9	-28.2
16 44 20.14	56 36 44.6	0.329	1.5	19.8,18.2,17.2,15.9,14.6	0.17	1.	4.7	9.5	–	1.3	-27.0
17 00 02.99	21 18 23.3	0.596	1.5	–, –, 17.4,15.9,14.9	1.4	0.	3.8	8.3	–	1.1	-28.1
17 00 56.01	24 39 28.2	0.509	1.5	16.8,16.8,16.0,15.3,14.3	10.	1.	8.7	10.3	–	0.7	-28.3
17 15 59.77	28 07 16.9	0.524	1.8	–, –, 17.2,15.8,14.6	0.32	1.	4.4	7.8	1.6	0.8	-28.0

^a The range from 1 to 2 reflects the ratio of narrow to broad emission lines.

^b The ratio of nuclear to host flux in r-band, from this work. Uncertainties are estimated to be 30%.

^c Strength of host galaxy interaction based on observed morphological features, as in paper 1.

^d 1/e profile flux drop

^e Total dynamic range of profile in magnitudes

^fFWHM of stellar images in arcsec

Table 2. 2MASS QSO sample comparisons

Property	2MASS QSOs			Blue QSOs
	$z < 0.3$	$z < 0.3, \text{luminous}$	$z > 0.3$	
Average z	0.2	0.2	0.4	0.2
Sample size	76	12	21	28
B-R	1.1	0.8	0.5	0.3
Nuc/Host	0.5	1.2	6.0	5.0
Int strong	33%	42%	14%	11%
Int (any)	75%	58%	81%	39%
Exp profile	16%	–	14%	18%
Bulge profile	20%	–	48%	54%
Messy profile	64%	–	38%	28%
Radio detected	40%	50%	29%	43%

Captions to figures

1. Sample selection in this paper ($z > 0.3$) and paper 1, from the full 2MASS sample observable from CFHT. Filled circles are the objects observed. Top: dashed lines are contours of constant luminosity. Bottom: spectral types range from broad to narrow emission lines, with intermediate values. Dashes are the full sample and dots are those observed. The paper 1 observed sample is grouped as types 1 and 2 only, as given in that paper.

2. Azimuthally averaged profiles of QSO 1715+281, with the CFHT PSF and also an HST image (with slightly different filter).

3. Images of representative objects from the sample, in decreasing levels of interaction - top left (1500+12) level 3, top right (1442+14) level 2, bottom (1715+28) level 1. The lower right is the HST image of the object at lower left. The images are 11 arcsec on a side except for the HST which is 6 arcsec.

4. Correlations with nuclear light fraction. Top: the type 1 objects have higher nuclear flux, consistent with the orientation expectation for broad-line objects. Bottom: With the high value exception, there is correlation with overall QSO colour, consistent with the nuclear fraction being reduced by dust reddening. In the lower panel, open dots are B-K and filled dots are 3(B-R). The line is the linear fit through all except the top right object.

5. Correlations with interaction level of host galaxies. The interaction scale was estimated on a 5-point scale but is reduced to 3 here to match the values from paper 1. Top: high levels of interaction are not seen in the highest redshift objects, presumably because of signal level and angular scale. Bottom: Highly interacting hosts have low flux nuclei, presumably because they are obscured by dust.

6. Fraction of hosts in different interaction levels in three redshift bins with about

equal sample numbers. There is a systematic change with redshift whereby lower redshift objects are more interacting. This may not all be due to detectability changes with redshift.











